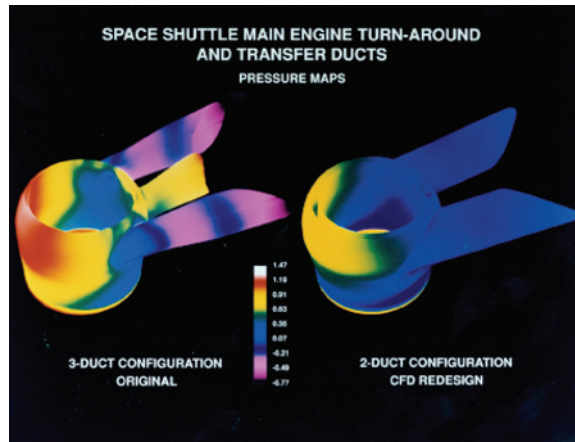


# The Impact of High-End Computing on the Space Shuttle Program

## Background

High-end computing and computational fluid dynamics (CFD) have played a key role in improving and enhancing Shuttle performance, reliability, and safety for more than two decades. The NASA Advanced Supercomputing (NAS) Division has been developing CFD-based high-fidelity design and analysis tools, which are being employed to help analyze today's problems, as well as guiding design decisions for future vehicles. The following captures some of the high-level, Shuttle-related events supported by the NAS Division and its supercomputing resources.

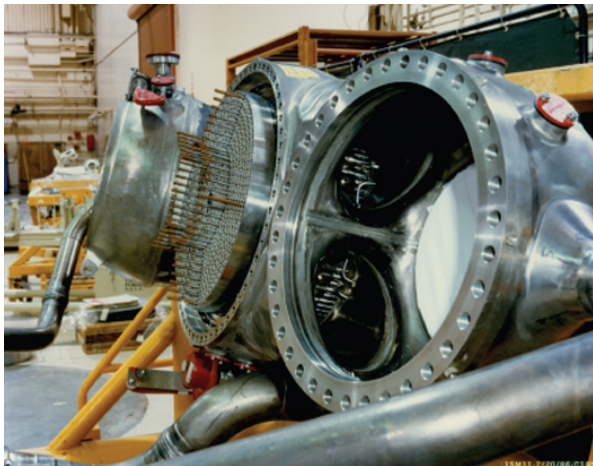


Shown here is a side-by-side comparison of the CFD analyses of the two- and three-duct hot gas manifold designs. White/red represents high pressure, while the blue coloring represents lower pressures. This redesign was the first instance of CFD having an impact in the area of rocket propulsion, and because high-end computing and CFD were so new at the time, code development and analysis were being conducted simultaneously. (Image generated by NASA Ames and Rocketdyne engineers)

series of enhancements, including major design changes to the hot gas manifold and turbopump.

The original three-duct hot gas manifold in the powerhead, considered the backbone of the SSME, was replaced by two enlarged ducts. The new two-duct design, facilitated with the use of Cray XMP and Cray 1 supercomputers, and CFD techniques developed by NAS researchers, enhanced overall engine performance and reliability. CFD analyses showed that the two-duct design reduced pressure gradients within the system, and lowered temperatures in the engine during operation, which reduces stress on the turbopump and main injector.

After undergoing extensive testing, the newly designed powerhead made its first flight on Discovery's 20th mission (STS-70) in July 1995, and has been used in all subsequent Shuttle missions.



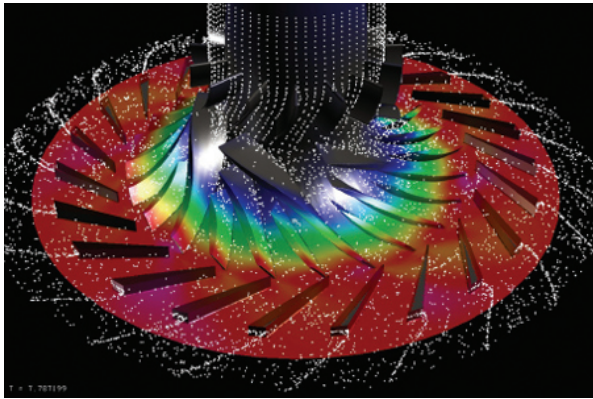
Pictured here is the re-designed two-duct hot gas manifold hardware (new powerhead design), which is considered the backbone of the Shuttle engine, and consists of the main injector and two pre-burners, or small combustion chambers, in addition to various propellant and oxidizer pumps, ducts, and lines. (Photo courtesy of Rocketdyne)

## Hot Gas Manifold Redesign

The Space Shuttle Main Engine (SSME), designed in the 1970s, is still the most sophisticated reusable rocket engine in the world today. Since its initial design, NASA has continued to increase reliability and safety of Shuttle flight through a

## Advanced Turbopumps and Flowliners

Since 1985, NASA researchers have been working to provide and enhance a computational framework for design and analysis of the entire fuel supply system of a liquid rocket engine (the Space Shuttle Main Engine's liquid oxygen and liquid hydrogen turbopumps, for example), including high-fidelity unsteady flow analysis.



A snapshot of particle traces and pressure contours resulting from the flow through the Space Shuttle Main Engine's impeller and diffuser. (Image generated by Tim Sandstrom/David Ellsworth, NASA Ames Research Center)

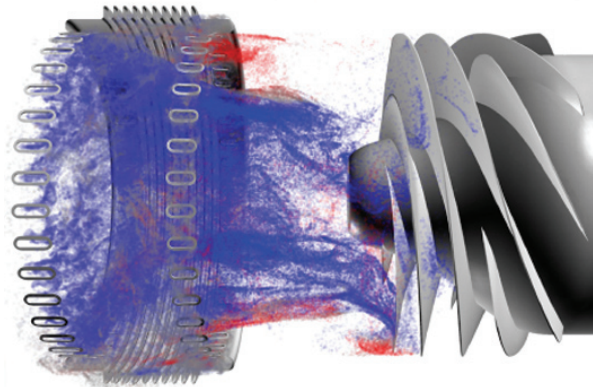


Illustration of unsteady interaction between the backflow and the flow in the bellows cavity—considered one of the major contributors to high-frequency cyclic loading. (Image generated by Tim Sandstrom/David Ellsworth, NASA Ames Research Center)

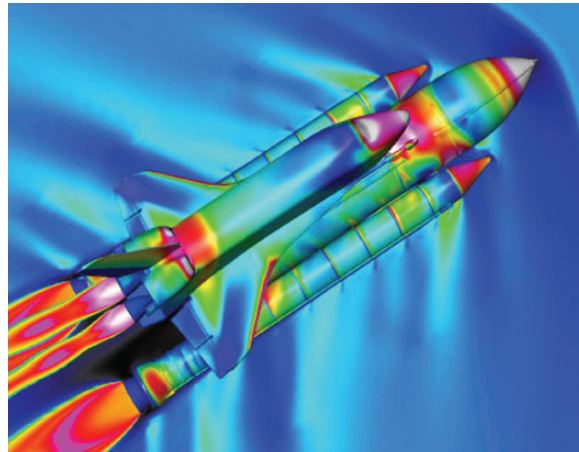
This effort decreases design costs, improves performance and reliability, and provides developers with information such as transient flow phenomena at startup, impact of non-uniform flows, and impact on the structure. Beginning in 2002, the computational framework was used to investigate the root cause of cracks in the Shuttle engine's fuel-line. In 2004, following the Columbia Shuttle accident, NASA CFD researchers participated in a NASA Engineering and Safety Center-sponsored independent technical assessment investigation of the Shuttle's fuel-line cracks. These results were combined with other analyses

and then presented to the Shuttle Program as part of the agency's Return to Flight efforts.

Various computational models have also been developed, and time-accurate computations carried out using this framework to characterize various aspects of the flow field surrounding the flowliner.

## Shuttle Ascent Analysis

OVERFLOW, a CFD program developed in the early 1990s for solving complex flow problems such as designing launch and reentry vehicles, has been applied to a number of Space Shuttle Launch Vehicle and Space Shuttle Orbiter issues over the past two decades. This CFD application has led to an overall better understanding of the aerodynamic loads on the Space Shuttle, and has served as the primary tool for verifying wind tunnel-derived aerodynamic loads during ascent including Orbiter wing, payload bay door, and vertical tail loads.



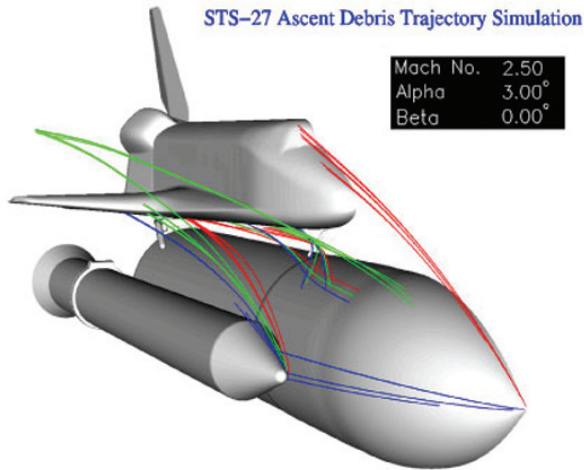
This image illustrates the OVERFLOW solution of the Space Shuttle Launch Vehicle flowfield at a Mach number of 1.25. The vehicle surface is colored by the pressure coefficient, and the color contours in the flowfield and plumes represent the local Mach number. (Image generated by Reynaldo Gomez, NASA Johnson Space Center)

Following the Shuttle flight STS-27R during which damage was incurred (launched and landed in December 1988), OVERFLOW was used to perform debris analysis. CFD results, which showed that only isolated potential debris sources existed on the vehicle, led to the determination that insulation and ice were the cause of the damage. This analysis has had a huge positive impact on the Space Shuttle Program, leading to increases in safety of flight by minimizing hazardous debris sources; reducing inspection time; minimizing damage on the next flight; and



reducing changes to thermal protection system application procedures.

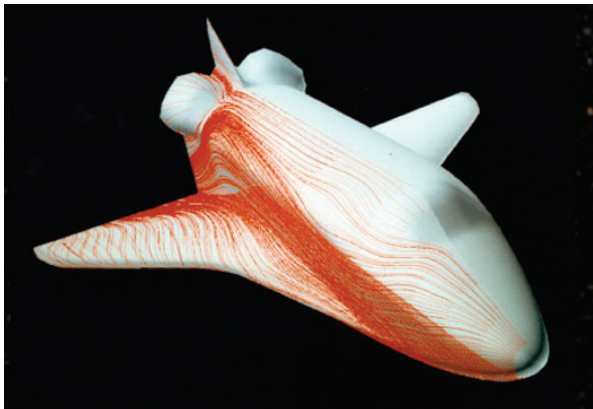
Throughout the 1990s, OVERFLOW was used to support the Shuttle Aerodynamic Loads Verification Program through CFD analysis of the Shuttle Launch Vehicle ascent aerodynamic loads environment. OVERFLOW solutions were used in conjunction with the flight data system, and provided data in areas not covered by flight instruments, yielding a cost savings of approximately \$10M.



Example of results obtained during analysis of debris trajectories done during flight STS-27R. Here, the flight conditions are at Mach 2.5 and three degrees angle of attack. (Image generated by Reynaldo Gomez, NASA Johnson Space Center)

## Shuttle Reentry Analysis

In 1984, NASA Ames CFD researchers obtained the first ever Navier-Stokes solution on an entire reentry vehicle using a Cray XMP supercomputer. Numerical results for turbulent flow around the complete configuration of the Shuttle Orbiter (including canopy, wing, orbital maneuvering system pods, and vertical tail) at a low supersonic

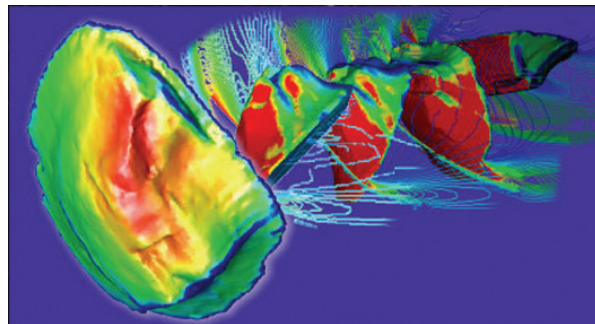


First ever Navier-Stokes solution of the complete configuration of the Shuttle Orbiter. Calculated at Mach 1.4 and zero degrees angle of attack. (Image generated by G. Bancroft and F. Merritt, Applied Computational Fluids Branch, NASA Ames Research Center)

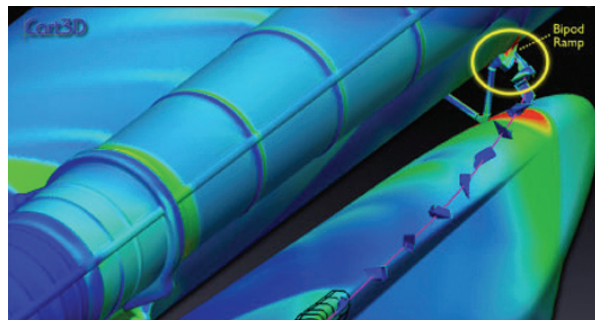
free-stream Mach number of 1.4 and a zero degree angle of attack was obtained by segmenting the flow field into four regions. Segmentation was advantageous in that it maximized the number of gridpoints, thus increasing resolution or detail of the numerical model. These numerical results, which showed good agreement with experimental data, paved the way for the more elaborate CFD analyses conducted following the Shuttle Challenger accident in January 1986.

## Columbia (STS-107) Accident Investigation

In response to the Columbia tragedy of February 1, 2003, the NAS Division employed state-of-the-art CFD codes to simulate steady and unsteady flow fields around Columbia during ascent. Simulation results prompted the use of a higher velocity and kinetic energy in foam impact testing done under the Columbia Accident Investigation Board, which showed massive damage to the Orbiter wing reinforced carbon-carbon panels and damaged T-seals due to foam impact. Simulations also provided insight into the mechanism of debris shedding from the bipod-ramp region. Each moving-body simulation required 1,000-5,000 processor hours running on a 1,024-processor SGI Origin supercomputer. Over a very short time period, more than 450 full simulations were run using about 600,000 processor hours.



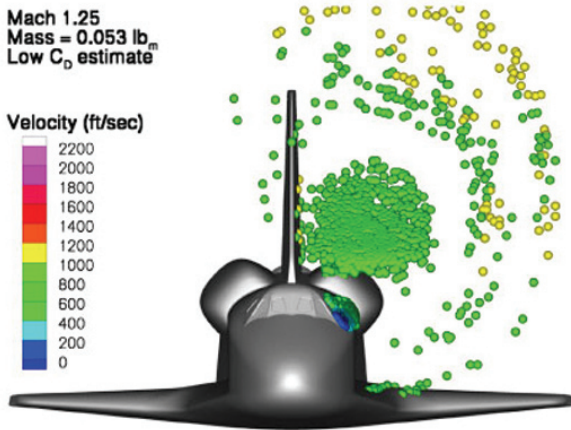
This image shows an unsteady Cart3D simulation used to predict the trajectory of a piece of tumbling foam debris released during ascent. The colors represent surface pressure. (Image generated by Scott Murman, NASA Ames Research Center)



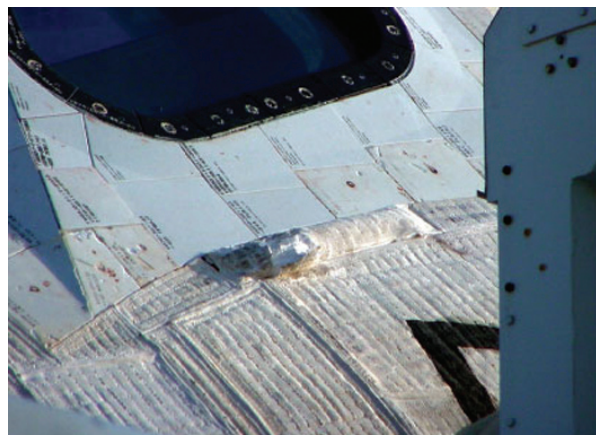
Show here: foam shedding from the bipod ramp region and its path to impact reinforced carbon-carbon panels on the Orbiter wing. (Image generated by Michael Aftosmis, NASA Ames Research Center)

## Discovery (STS-114) Mission Support

During the Discovery mission (summer 2005), NAS Division researchers were on stand-by to provide debris transport analysis support using the NASA Ames-developed debris-transport software running on the 10,240-processor SGI Altix supercomputer, Columbia. Several incidences throughout the mission required NAS resources:



An example of the CFD-based debris-transport analysis conducted on the torn Advanced Flexible Reusable Surface Insulation blanket, showing probable impact locations for debris of a certain size at a certain flight condition (velocity). Results from CFD analyses were used to establish flow conditions (for example, Mach number and angle-of-attack) for wind tunnel tests conducted to gather more extensive information about the torn blanket. (Image generated by Reynaldo Gomez, NASA Johnson Space Center)

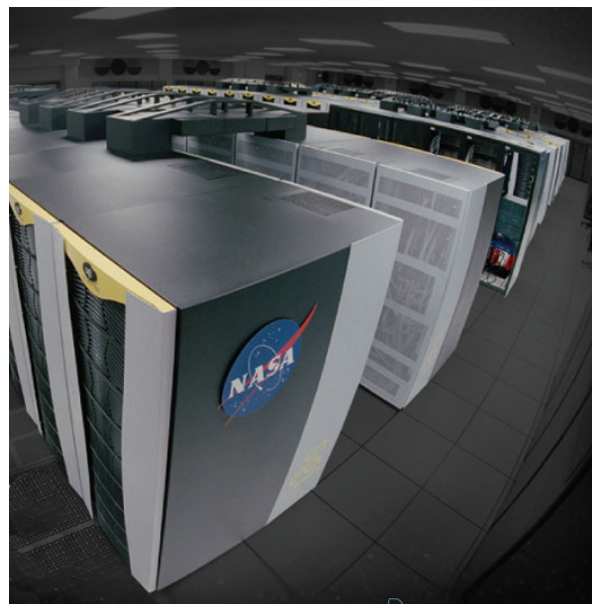


Post-flight photo of the torn 20 x 3 inch panel of the Advanced Flexible Reusable Surface Insulation blanket located under the commander's window on the Discovery Shuttle. (Image courtesy of NASA Orbiter Ops and Project Mgmt Office)

- Evaluation of the potential threat from ice forming on one of the solid rocket boosters/ external tank (SRB/ET) aft attach struts on launch day. The ice was a resultant of liquid nitrogen leaking from the ground umbilical connector plate on the ET. Debris simulations were run on Columbia and reported to NASA Johnson within 90 minutes. The threat never materialized, as the final ice inspection from NASA Kennedy reported that no ice was present on this strut.

- Analyses of ice/frost ramp foam debris that were shed 155 seconds into the mission. Within several hours from being tasked by NASA Johnson to analyze the threat of a potential hit on the starboard wing of the Orbiter, NAS researchers delivered an analysis of a complete set of debris simulations indicating that this debris would not cause damage. This conclusion was reinforced by a detailed examination of the on-orbit inspection results, which showed that this debris did not cause any damage to Orbiter tiles or reinforced carbon-carbon panels.

- Analyses of a torn 20 x 3 inch panel of the Advanced Flexible Reusable Surface Insulation blanket located under the commander's window on the Discovery Orbiter using both the debris-transport analysis software and wind tunnel tests. Results indicated that fraying and incremental erosion was the primary failure mode, and large debris fragments were unlikely (which would have resulted in another extravehicular activity).



The Columbia supercomputer is a 10,240-processor SGI Altix system with a 51.9 trillion-per-second processing capability. Columbia is currently the agency's main supercomputing resource for NASA missions.

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